Objects in a social world: Infants' object representational capacity limits are shaped by objects' social relevance

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Abstract

Several decades of research have revealed consistent signature limits on infants' ability to represent objects. However, these signature representational limits were established with methods that often removed objects from their most common context. In infants' everyday lives, objects are very often *social artifacts*: they are the targets of agents' goal-directed actions, communications, and beliefs, and may have social content or relevance themselves. In this chapter, we explore the relationship between infants' object representational capacity limits and their processing of the social world. We review evidence that the social content and context of objects can

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shift infants' object representational limits. We discuss how taking the social world into account can yield more robust and ecologically valid estimates of infants' early representational capacities.

1. Introduction

As infants move around their environments, and as objects and people move around them, infants must be able to encode and store representations of objects that are no longer in view to maintain a stable representation of the world. Take, for example, an infant who observes her ball roll behind her toy car. To keep playing with the ball, she must be able to track the trajectory of the ball and represent the ball even though she can no longer see it. She can then decide to take an action—say, crawling over to retrieve the ball—without continual visual access to the ball. The ability to maintain stable, lasting representations of the world is critical for infants to learn from their environments and to understand the actions of the objects and the people around them.

Research on infants' ability to represent objects that are no longer in view has revealed two signature capacity limits. First, infants' capacity to represent *what an object looks like* (i.e., an object's features, like its color or shape) is extremely limited, but this capacity increases across the first year of life, from one object representation with featural information at 6 months, to two at 9 months, to around two to three by 12 months (Káldy & Leslie, 2003, 2005; Kibbe & Feigenson, 2016; Kibbe & Leslie, 2011, 2013, 2016, 2019). Second, infants have a firm capacity limit of three individual objects that they can represent concurrently, regardless of whether they represent the objects' features (Feigenson & Carey, 2003, 2005; Feigenson, Carey, & Hauser, 2002; Kibbe & Feigenson, 2016; Van de Walle, Carey, & Prevor, 2000; vanMarle, 2013). If they are tasked with representing more than three individual objects concurrently, their representations fail catastrophically and they are unable to represent even a subset of the objects in the hidden array (e.g. Feigenson & Carey, 2003, 2005). This three-object limit is observed across infancy, easing only in toddlerhood (e.g. Barner, Thalwitz, Wood, Yang, & Carey, 2007; Kibbe & Feigenson, 2014). Both signature limits have been observed consistently, using a range of methods (e.g., in which objects are hidden from infants behind occluders or inside containers) and dependent measures (e.g. looking time when an occluded object is revealed, searching time in a location). Importantly, these signature limits present a significant information-processing bottleneck for infants. Because infants are limited in how much information they can hold in mind concurrently, these capacity limitations in turn limit their ability to process and keep track of complex and dynamic scenes.

The methods used to assess infants' representational capacity limits, by design, removed objects from their most common context in infants' lives: the social environment. In the real world, objects may have social content or significance, and are often the targets of agents' goal-directed actions, communications, and beliefs. When objects are *socially relevant*, attending to and processing social scenarios may influence the way infants attend to, process, and represent objects.

The goal of this chapter is to explore the relationship between infants' object representational capacities and their processing of the social world. We begin by reviewing the two signature limits on infants' object representational capacities. We next describe some of the ways in which infants differentiate objects and agents, and process the relationships between objects and the agents that interact with those objects. Finally, we review evidence that suggests that objects' social significance impacts signature limits on infants' object representational capacities.

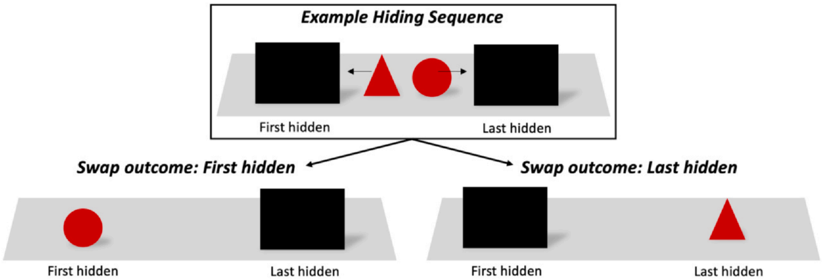
2. Two signature limits on infants' object representational capacities

In this section, we describe two signature limits on infants' object representational capacities. We focus specifically on infants' capacity to represent real, physical, three-dimensional objects (and not, e.g., two-dimensional images of objects; see Kibbe, 2015; for discussion), because these objects make up infants' environments and are the targets of infants' own actions and the actions of social agents.

2.1 Signature limit 1: Infants' capacity to represent objects' identities

Infants' capacity to remember the identifying surface features (e.g. color, shape) of occluded three-dimensional objects has been examined primarily using violation-of-expectation methods (for an overview of the logic of violation-of-expectation studies, see Stahl & Kibbe, 2022). In these studies, infants were familiarized to a small number of three-dimensional objects that differed on a single feature (e.g. two shapes, Káldy & Leslie, 2005; Kibbe & Leslie, 2011; *or* two colors, Káldy & Leslie, 2005). During test trials, the objects were placed on the stage in full view, and then moved sequentially behind separate occluders. Infants' representations of what was hidden behind each occluder was tested by removing one of the occluders and revealing either the object that was hidden in that location originally (the *control* outcome) or the unexpected other object (the *swap*) outcome, and measuring infants' looking duration to each outcome. If infants maintained a representation of the featural identity of the object that was hidden behind the screen, they should look longer when a different object is revealed instead. A 2D schematic of an example study of this type is shown in Fig. 1.

At 6 months, infants tested on the last-hidden location look longer when the object is revealed to have changed its identifying features (Káldy & Leslie, 2005; Kibbe & Leslie, 2016), suggesting they retained the features of this object in their representation of what was hidden in that specific location. However, when 6-month-old infants are tested on their representation of what was hidden in the *first* location, infants' looking patterns do not differ between control and swap outcomes; they consistently fail to represent the identifying features of the object hidden in this location (Káldy & Leslie, 2005; Kibbe & Leslie, 2011, 2016). Infants' failure to remember the features of the first-hidden object is not due to memory decay; when 6-month-olds are tasked with remembering only one object



Number of objects:	2 objects		3 objects	
Object Hidden:	First	Last	2nd-to-last	Last
6 months	✗	✓		
9 months	✓	✓	✗	✓
12 months			✓	✓

Fig. 1 Schematic drawing of a typical hide-and-reveal sequence and infants' pattern of successful detection of a feature change, as evidenced by their look durations to "swap" outcomes, in which the originally-hidden object is revealed to have changed features, compared to "control" outcomes, in which the originally-hidden object is revealed.

for the same duration as it would take to hide the second object, they succeed (Káldy & Leslie, 2005). Instead, the attentional demands of tracking the second object into occlusion appear to drive this pattern (Kibbe & Leslie, 2013; Kibbe, 2015).

By 9 months, these limitations begin to ease, likely due to developmental increases in endogenous attentional resources (Colombo, 2002; Kibbe & Leslie, 2013). Nine-month-old infants can remember the features of *both* of the hidden objects (Káldy & Leslie, 2003; Kibbe & Leslie, 2013). But 9-month-olds' ability to remember object features also is limited by the attentional demands of the task; when infants are tasked with remembering the features of the second-to-last hidden of *three* objects, they fail to remember the features of this object. This contrasts with 9-month-olds' ability to remember the second-to-last-hidden object when only two objects were hidden in a trial, suggesting that the additional demands of tracking a third object into occlusion reduces the attentional resources available to represent object features. By 12 months, infants can robustly remember the features of both the last-hidden and second-to-last-hidden objects even when tasked with tracking three objects (Kibbe & Leslie, 2013).

Together, this work reveals a consistent signature limitation on infants' ability to represent the features of objects (summarized in Fig. 1). Infants' ability to represent objects' featural identities is extremely limited, to a maximum of one identity at 6 months, a maximum of two object identities at 9 months, and around two to three object identities at 12 months. Infants' ability to represent object features is limited by both the attentional demands of the task, and by infants' own available attentional resources, which are undergoing continual development across the first year. These limits persist at least into the third year of life (Kibbe & Applin, 2022).

2.2 Signature limit 2: Infants' capacity to represent quantities of objects

When infants fail to remember the features of hidden objects, not all is lost. Infants can keep track of *how many* objects are hidden, even if they are unable to remember exactly what the objects look like. For example, while 6-month-old infants consistently fail to represent the features of the first-hidden of two objects, they nevertheless expect that the object should continue to exist behind the occluder, and are surprised and look longer if the object vanishes completely (Kibbe & Leslie, 2011), suggesting infants can represent individual objects without necessarily representing the objects' identities (see also Kibbe & Feigenson, 2016; Zosh & Feigenson, 2012).

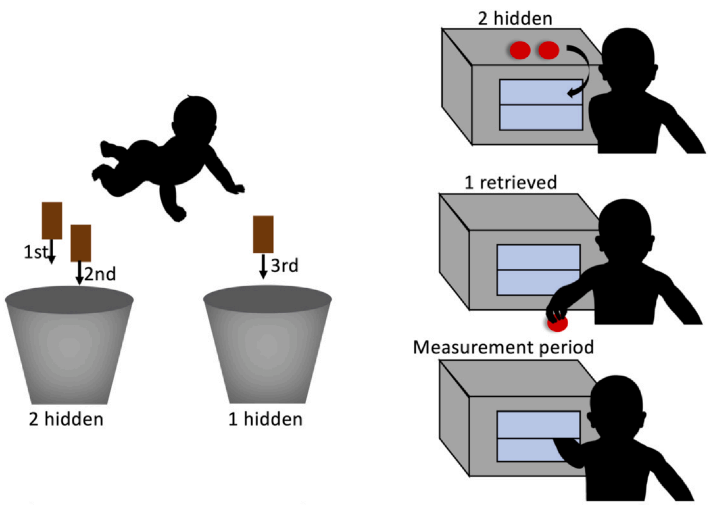
However, infants' ability to represent *how many* objects comes with its own limit. Previous work has investigated infants' capacity for representing multiple objects concurrently using a range of methods, including ordinal choice (e.g. Feigenson & Carey, 2005; Feigenson et al. 2002; vanMarle, 2013), manual search (e.g. Feigenson & Carey, 2003; Van de Walle et al., 2000), and violation of expectation (Kibbe & Feigenson, 2016; Moher & Feigenson, 2013) all of which have yielded consistent results.

In the ordinal choice task, infants observe an experimenter distributing edible objects one at a time (typically graham cracker segments) into two opaque containers. After the objects are distributed, one of the containers has more individual crackers than the other container. The experimenter then invites infants to retrieve the contents of one of the containers by prompting infants using neutral language (e.g. "What can you find?"). The dependent measure is which container the infant chooses. In these tasks, when the quantities in either container do not exceed three crackers (e.g. one vs. two crackers, one vs. three crackers, or two vs. three crackers), infants consistently choose the container with the larger number of crackers (Feigenson et al., 2002; vanMarle, 2013; vanMarle & Wynn, 2011). However, if the quantity in one of the containers exceeds 3 (e.g. 1 vs. 4 crackers, or even 2 vs. 8 crackers), infants choose the containers at roughly equal rates (Feigenson & Carey, 2005; vanMarle, 2013). Some of these results are summarized in Fig. 2, left panel.

Similar results have been observed using manual search tasks (see Fig. 2, right panel). In these tasks, an experimenter hides a number of identical objects inside of an opaque box through a fabric slit in the box's front. The box is constructed so that infants can reach inside of the box, but are unable to see the contents of the box. After the object(s) are hidden, infants reach into the box through the front opening and retrieve either all of the hidden objects ("expected empty" trials) or only a subset of the hidden objects (the experimenter surreptitiously holds back the remaining objects through a hidden opening in the back of the box; "more remaining" trials). This is followed by a 10 s measurement period in which infants are allowed to search inside the box. The dependent measure is infants' search time—if infants expect more objects are inside of the box, they should search inside of the box for those missing objects longer than they would search if they believe that there are no additional objects inside.

Previous work using this method has found that when one, two, or three identical objects are hidden inside the box, infants appear to be able to represent the number of objects hidden with high precision. For example, Feigenson and Carey (2003) found that when one object was hidden inside of a box and infants were allowed to retrieve it, infants' searching in the box after the object's retrieval was relatively short. When two or three objects were hidden inside the box, and infants were allowed to retrieve all but one of the objects, they searched longer during the measurement period. Furthermore, when infants were then allowed to retrieve the remaining object, they once again decreased their searching, suggesting they were representing the exact number of objects that were hidden and had tracked precisely how many objects had been hidden, how many had been removed, and how many were still inside the box. However, Feigenson and Carey (2003) found that when four objects were hidden inside of the box, infants searched similarly on "expected empty" and "more remaining" trials, suggesting that they were unable to keep track of the precise number of objects that were hidden when that number exceeded three, similar to their failure in the ordinal choice task. Some of these results are summarized in Fig. 2, right panel.

Final converging evidence for this striking limit comes from violation-of-expectation looking time tasks. For example, Wynn (1992) showed 5-month-old



Number hidden	Success?
2 vs. 1	✓
3 vs. 1	✓
4 vs. 1	✗

Number hidden	Success?
2	✓
3	✓
4	✗

Fig. 2 The left panel shows a schematic of the ordinal choice task and infants' pattern of successful crawling to the bucket containing the larger quantity, up to three objects. The right panel shows a schematic of the manual search task and infants' pattern of successfully tracking the number of individuals hidden inside the box, up to three objects (as indexed by their search patterns during the measurement period).

infants arrays of two identical objects, which were then occluded. Infants then watched the experimenter remove one of the objects. The occluder was then lifted to reveal one object (numerically consistent outcome) or two objects (numerically inconsistent outcome). Infants looked longer at the numerically inconsistent outcome, suggesting they tracked and updated the precise number of objects that were present in that location (see also Bremner et al., 2017; Christodoulou, Lac, & Moore, 2017; Koechlin, 1997; Simon et al., 1997). By contrast, Kibbe and Feigenson (2016) showed 13-month-old infants sets of four objects which were then hidden behind a single occluder. None of the objects were shown to be removed during the occlusion period. The screen was then removed to reveal either four objects (numerically consistent outcome), or only three objects (numerically inconsistent outcome). Infants failed to notice when the quantity of the objects had changed, as evidenced by their roughly equal looking times to the two outcomes.

Together this work suggests that, when infants are tasked with tracking four objects in a location, their representational capacities appear to fail "catastrophically", and they are unable to represent even a subset of the hidden objects (see Zosh & Feigenson, 2009, for discussion). Interestingly, this strict three-object limit, with catastrophic failures of representation beyond three, is remarkably consistent across infancy, observed in infants as young as 9 months (e.g. Feigenson et al. 2002), and begins to ease in toddlerhood (Barner et al., 2007; Kibbe & Feigenson, 2014).

However, under some circumstances infants can overcome this three-object limit. Infants can take advantage of cues that help them to restructure their representations of objects into more manageable groups, or chunks, to help them keep track of more than three objects in a given location. Infants have been shown to successfully track four individuals when those individuals could be chunked into two groups of two using a variety of perceptual cues, including spatial groupings (Feigenson & Halberda, 2004; Moher, Tuerk, & Feigenson, 2012; Rosenberg & Feigenson, 2013), as well as conceptual and categorical cues (Feigenson & Halberda, 2008), and statistical regularities (Kibbe & Feigenson, 2016). We will return to this in Section 4.

3. The social significance of objects

For humans, objects very often are tools we use, the toys we play with, the foods we eat. A young infant who encounters a particular object rarely experiences only the object's perceptual features (its location, color, shape, etc.). They may be sensitive to whether an object's features mark it as a *social kind*, like a doll. Or, they may experience the object in relation to another agent. For example, they may encounter a situation in which an agent wants to retrieve this object over another (Luo & Baillargeon, 2005; Woodward, 1998), or an agent has (or does not have) visual access to the object (Kampis, Parise, Csibra, & Kovács, 2015; Luo & Baillargeon, 2007; Woodward, 2003; Wu & Kirkham, 2010), or an agent is communicating something about the object (Krehm, Onishi, & Vouloumanos, 2014; Sodian & Thoermer, 2004; Thoermer & Sodian, 2001; Woodward & Guajardo, 2002) or is labeling the object (LaTourrette & Waxman, 2020; Pomiechowska, Bródy, Csibra, & Gliga, 2021), or an agent has an emotional disposition toward the object (Mumme & Fernald, 2003; Repacholi, 1998). As infants develop, they may represent even more sophisticated relationships between objects and agents, including object ownership (Blake & Harris, 2011; Brownell, Iesue, Nichols, & Svetlova, 2013; Saylor, Ganea, & Vázquez, 2011), pretense (Leslie, 1987; Onishi, Baillargeon, & Leslie, 2007; Walker-Andrews & Kahana-Kalman, 1999), and false beliefs about objects' locations or identities (Kampis & Kovács, 2022; Onishi & Baillargeon, 2005; Senju, Southgate, Snape, Leonard, & Csibra, 2011). In all of these social contexts, objects' features and locations both play a role in processing their social relevance. Here, we give a brief overview of some of these studies.

From birth, infants prefer looking at faces or face-like stimuli over non-face stimuli (e.g., Farroni et al., 2005; Johnson, Dziurawiec, Ellis, & Morton, 1991; Valenza, Simion, Cassia, & Umiltà, 1996). Infants quickly learn to recognize familiar faces (e.g., Field, Cohen, Garcia, & Greenberg, 1984; Walton, Bower, & Bower, 1992), and they individuate faces from non-faces (Bonatti, Frot, Zangl, & Mehler, 2002). However, having a face is not the only cue infants use to determine social agency. For example, infants infer that objects that move independently (e.g., Luo & Baillargeon, 2005; Luo, Kaufman, & Baillargeon, 2009; Spelke, Phillips, & Woodward, 1995; Surian & Caldi, 2010), interact contingently (Johnson, Slaughter, & Carey, 1998; see Johnson, 2003 for review), and/or behave rationally (e.g., Gergely, Nádasdy, Csibra, & Bíró, 1995; see Gergely & Csibra, 2003 for review) are animate social agents with goals and intentions. Thus, social content drives infants to detect agents in their environments.

Once infants recognize the presence of social agents, they demonstrate understanding of their goal-directed actions (Choi, Mou, & Luo, 2018;

Luo, 2011; Woodward, 1998). In Woodward's (1998) classic study, infants observed an agent reach toward and grasp one of two different toys (e.g. a bear and a ball). Across multiple trials, the agent consistently grasped Toy A and not Toy B. At test, the locations of the objects were switched, and the agent reached for either Toy A in its new location (new reach path, familiar target) or Toy B in its new location (old reach path, novel target). Infants looked longer when the agent reached for Toy B, suggesting they expected the agent to behave consistently toward the object, regardless of its location. Infants also make predictive gaze shifts to the target object prior to the agent's reach, suggesting that they anticipate the agent's actions and are not merely reacting to the agent's actions on the objects at test (Cannon & Woodward, 2012; Kim & Song, 2015). In order to represent and make predictions about an agent's goal-directed actions on objects in these studies, infants must notice that the two objects differ in featural identity, notice that the agent consistently grasps one object over the other, and store this agent-object association in long-term memory (Buresh & Woodward, 2007; but see Kampis et al., 2013). The featural identities of the objects therefore play a crucial role in infants' ability to process the social scene. Object features are also imbued with particular importance when infants receive communicative signals about an object—when an agent points at (as opposed to reaches for) an object, they are more likely to remember the object's features than they are the object's location (Okumura, Kanakogi, Kobayashi, & Itakura, 2020; Yoon, Johnson, & Csibra, 2008; but see Silverstein, Gliga, Westermann, & Parise, 2019; for a review of the role of communicative intentions in infants' information processing, see Csibra & Gergely, 2009; Csibra, 2010). In this case, social context impacts what infants encode about objects.

Not only do infants detect agents' intentions, they are highly sensitive to whether those agents have visual access to objects, and take others' visual perspectives into account when reasoning about agent's actions. For example, by at least 3 months of age, infants expect that agents should not act on objects they cannot see (Choi et al., 2018; Southgate & Vernetti, 2014). By at least 4 months, infants show enhanced encoding of objects that are the targets of an agent's gaze (e.g. Michel, Wronski, Pauen, Daum, & Hoehl, 2019; Reid, Striano, Kaufman, & Johnson, 2004; Wahl, Michel, Pauen, & Hoehl, 2013).

Other agents' perspectives may in fact take precedence over or supplant infants' own representations of hidden objects. For example, Kampis et al. (2015) found that infants showed neurophysiological evidence of representing a hidden object (as measured by EEG) both when the object was actually hidden, and when an agent *believed the object to be hidden* but did not see that the object had been removed from the scene (see also Forgács et al., 2019). In a behavioral study (Kampis, 2017), infants watched multiple objects being hidden in a location while an agent looked on. The infant then observed all of the objects being removed, while the agent observed all, or *all but one,* of the objects being removed. Infants searched the location longer when the agent had observed only a subset of the objects being removed, compared to when the agent had observed all of the objects being removed, suggesting that the agent's belief about the quantity of the objects in the box influenced infants' own behaviors. These results suggest a potential influence of an agent's visual access to the contents of a location on infants' representations of object quantities (see also Kampis & Kovács, 2022). Indeed, Southgate (2020) proposed that infants have an "altercentric bias". She argued that infants are highly sensitive to others' perspectives, while simultaneously lacking efficacy to act on the world, with the result that others' perspectives take precedence over, or even supplant, infants' own perspectives. This leads to the prediction that, as infants develop a greater sense of self, the altercentric bias eases somewhat, and other agents' perspectives are less likely to supplant infants' own perspectives (see Kampis & Southgate, 2020; for review).

4. How the social world shapes infants' capacity limits

Thus far, we have reviewed an abundance of research that reveals infants' signature object representational capacity limits (in non-social contexts), and their understanding of the social content of objects and the social contexts in which objects frequently appear. In recent work, we have been exploring how infants' seemingly robust and consistent object representational capacity limits may in fact be impacted by the social content and context of objects. In this section, we describe a series of recent papers from our labs demonstrating that *what* infants remember about objects, and *how many* objects they can remember, both are influenced by the social content and context of objects.

4.1 The social world shapes infants' capacity to represent object identities: Representing social kinds

Infants' representational limits on encoding object identities shift when objects have socially relevant identities. Recall that previous work showed that 6-month-old infants typically are only able to represent the featural identity (e.g., triangle) of the more recently hidden of two hidden objects when the objects were featurally distinct (Káldy & Leslie, 2005), but fail to represent the featural identity of the first-hidden object (Kibbe & Leslie, 2011; Fig. 1), a signature limit on 6-month-olds' object representational capacities. Kibbe and Leslie (2019) asked whether 6-month-olds could encode the identities of both objects if, instead of being merely featurally distinct from each other, the objects also were from distinct *socially relevant categories*. We first familiarized infants to two objects, a human-like doll's face and a non-human-like ball. Thus, the objects were featurally distinct, but also from distinct socially relevant categories. At test, we hid the objects sequentially, and then lifted the occluder hiding the *first-hidden object* to reveal either the original hidden object (e.g. doll hidden, doll revealed; or ball hidden, ball revealed; *control* outcome) or that the objects had swapped places (e.g. doll hidden, ball revealed; or ball hidden, doll revealed; *swap* outcome) (see Fig. 3, left panel). We found that 6-month-olds looked significantly longer at the swap outcome, suggesting that they remembered the identity of the first-hidden object and were surprised that it was revealed to have changed. A follow-up study confirmed that it was the categorical identities between the objects, and not simply the features of the objects, that was driving infants' success: when the doll's face was inverted, disrupting infants' ability to process the object as a human-like face (Farroni et al., 2005; Southgate et al., 2008), infants showed the typical pattern of failure.

Finally, we asked whether the categorizability of the objects helped infants to encode what the objects looked like. We reasoned that, since the objects' features are relevant to identifying the objects' categories, infants may be better able to encode the objects' features into their object representations than when objects did not come from distinct social categories (as in previous work, e.g., Kibbe & Leslie, 2011). We again hid the ball and the doll's face. However, this time when we removed the occluder hiding the first-hidden object, infants saw either the control outcome, or that the object had changed to a *featurally distinct object from the same category* (e.g., red and yellow striped ball hidden, green and blue polka-dot ball revealed; or brown-skinned, brown-eyed, bald baby hidden, pink-skinned, blonde-haired, blue-eyed child doll revealed; see Fig. 3, left panel). Infants looked roughly equally at the control and swap outcomes, suggesting that even though they were able to encode the *categorical* identities of the objects, they were unable to encode the objects' surface features, consistent with previously observed feature encoding limits in 6-month-olds.

These results, summarized in Fig. 3, suggest that representing object categories may be relatively less costly than representing the object's surface features, which requires sustained attention (Kibbe & Applin, 2022; Kibbe & Leslie, 2013). For infants with limited attentional and representational resources, representing objects' socially relevant categorical identities expands their representational capacities, allowing them to remember more than they could otherwise, even if it is at the expense of remembering exactly what an object *looks like*. While some evidence suggests that older infants may represent object's categories as long as they know their categories (even if the categories are non-social, like cup or car; Kibbe & Stahl, under review; Pomiechowska et al., 2021), for very young infants with no expressive vocabulary, very limited receptive vocabulary, and limited knowledge, we speculate that *social* categorical distinctions between objects may be the primary way infants encode objects in order to make the most of their limited representational resources. That is, while infants are limited in the surface features they can encode and represent, objects' social content helps infants expand those representational limits to represent more information than they could otherwise.

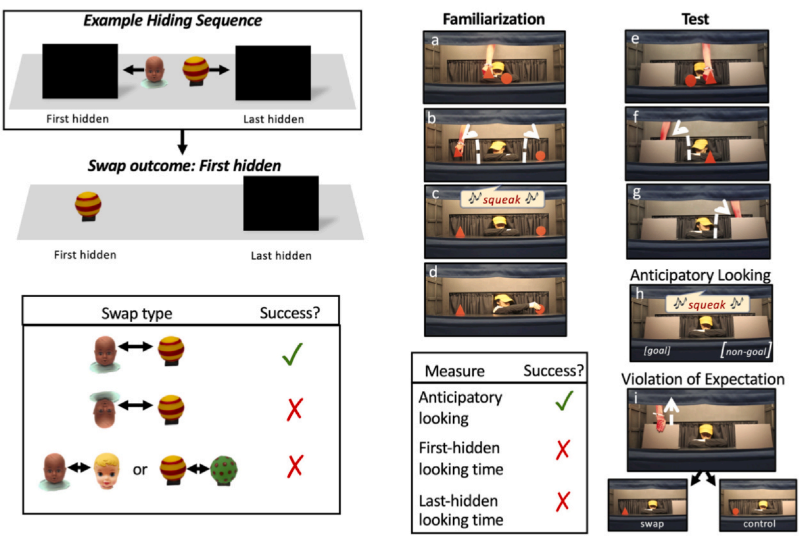


Fig. 3 Left panel shows a schematic of an example first-hidden test trial from Kibbe and Leslie (2019) (top left), and 6-month-olds infants' pattern of successfully detecting a change to the identity of the first-hidden object (bottom left). Right panel shows a schematic of an example familiarization trial (panels a–d) and an example first-hidden test trial (panels e–i) from Applin and Kibbe (2019). The inset in the right panel shows 6-month-old infants' pattern of success on the anticipatory looking measure and the looking time measures.

4.2 The social world shapes infants' capacity to represent objects' identities: Representing agents' object-directed goals

Infants' representational limits also shift when objects are placed in a social *context*. Recall that previous work showed that infants are sensitive to agents' goal-directed actions toward objects, and make predictions about agents' future actions on objects based on agents' past preference for some objects over others (Cannon & Woodward, 2012; Kim & Song, 2015; Woodward, 1998; see Section 3.1 for discussion). Applin and Kibbe (2019) asked whether the goal-relevance of the objects' features would influence the way 6-month-old infants represent occluded objects. Specifically, we asked whether 6-month-old infants who witness an agent preferentially reaching for one object over another would subsequently be more likely to encode the features of that object, even when the object was the *first-hidden* of two objects.

We combined the method of Woodward (1998) with the method of Kibbe and Leslie (2011). In our study, infants viewed a series of four Familiarization trials in which an experimenter placed two featurally distinct objects (a disk and a triangle, the same objects used in Kibbe & Leslie, 2011) on a stage in view of an agent who was seated behind the stage floor (see Fig. 3, panel a). The experimenter then moved the objects to the back of the stage while the agent followed the trajectories of the objects with her eyes and head (Fig. 3, panel b). The experimenter then played an auditory cue (a squeaking sound, Fig. 3, panel c), after which the agent reached for and grasped one of the two objects (Fig. 3, panel d). The order in which the objects were placed and the positions of the objects were counterbalanced across trials, so that infants could not form any long-term associations between a particular object and a particular location. However, the agent always reached for and grasped the same object on each trial regardless of its spatial location, so that infants could form long-term associations between the agent and a particular object.

The four test trials proceeded similarly to the studies described in Section 2.1 (see Fig. 1), except that the agent was present. The experimenter placed the two objects on the stage (Fig. 3, panel e) and then moved the objects behind separate occluders, such that they were visible to the agent but not visible to the infant (Fig. 3, panels f–g). Importantly, *the goal-relevant object was always hidden first*. This was a crucial aspect of the design, since 6-month-olds fail to represent the features of the first-hidden of two objects in non-social contexts (see Section 2). After the objects were occluded, infants heard the short auditory cue (Fig. 3, panel h), and then the experimenter removed one of the occluders (either the occluder hiding the first-hidden goal object (see Fig. 3, panel i), or the occluder hiding the last-hidden, non-goal object) to reveal either the control or the swap outcome. The agent did not take any action during test trials.

We had two dependent measures: infants' anticipatory looks (the direction of infants' first look following the auditory cue) and infants' looking times to the different outcomes after the occluder was removed. We predicted that 6-month-old infants would prioritize encoding the features of a goal-relevant object instead of, or in addition to, the other object in the array, and should therefore predict where the agent will reach for her goal object (even though the goal object was hidden first) as evidenced by their anticipatory looks following the auditory cue, and also should look longer when the goal object is revealed to have changed features. Consistent with this, we found that 6-month-old infants made anticipatory looks to the goal location at rates significantly above chance, suggesting they expected the agent to reach toward the occluded first-hidden goal object. However, contrary to our predictions, we also found that infants failed to notice when *either* of the objects was revealed to have changed shape, as evidenced by their roughly equal looking times to control and swap outcomes. That is, they failed to represent the features of *either* the first-hidden *or* the last-hidden object on each trial, a pattern that we did not predict.

What drove this surprising pattern of results? Six-month-olds were able to learn the relationship between the agent and the objects' featural identities (e.g. the *disk* and not the *triangle*) and store this relationship in long-term memory. They were then able to use this memory to generate an action prediction, anticipating where the agent would reach for her object *even though the relevant object was occluded and was hidden first.* However, we suggest that representing and maintaining this action prediction came at a cost to representing the specific contents of the scene in that moment. Having limited representational resources, infants allocated those resources to representing the agent and her action, and maintaining that representation as objects are occluded, rather than to representing the specific identities of each hidden object on each trial. That is, for 6-month-old infants, on a moment-to-moment basis, representing *people and their actions* is prioritized over representing objects—even objects whose features they would typically be able to represent (i.e. the last-hidden of two objects; see Fig. 1).

Together, these results suggest that the "signature limit" on infants' ability to represent object identities may be more flexible than previously thought. When objects are *socially relevant*, infants' ability to encode objects' identities is influenced by both the social content and context of objects. Infants may remember more or fewer object identities, depending on the social factors at play.

4.3 The social world shapes infants' capacity to represent object quantities: Hierarchical restructuring of object representations

As discussed in Section 2, infants are able to maintain representations of three hidden objects, but fail to remember four hidden objects. However, infants can hierarchically reorganize their memory representations into chunks, thereby allowing them to overcome the three-item limit to remember more objects (e.g., Feigenson & Halberda, 2004; 2008; Kibbe & Feigenson, 2016). In a series of studies (Stahl & Feigenson, 2014; 2018; Stahl, Pareja, & Feigenson, 2023), we have investigated whether social information impacts 16-month-old infants' ability to restructure their representations of hidden objects in order to keep track of more than they otherwise could.

Using the manual search method, we presented 16-month-olds with four identical objects. However, instead of using inanimate, non-social objects (e.g., balls, shapes, cars), we used human dolls. As in previous studies, we placed four dolls equally spaced on top of the box prior to hiding. For one group of infants, the dolls were placed atop the box facing outward, then were turned toward each other in pairs and greeted each other by saying "hello" to one another (Fig. 4, panel a). In this case, the dolls looked at and interacted contingently with each other within a pair. For the other group of infants, the dolls were placed atop the box facing each other in pairs, then were turned outward to face the infant, and greeted the infant by saying "hello" (and thus the number of movements and utterances were identical across conditions) (Fig. 4, panel b). We then hid all four dolls inside of the box, and infants were allowed to retrieve a subset of the dolls, or all of the dolls. We found that 16-month-olds only searched longer when more dolls remained inside of the box (relative to when the box was empty) in the condition in which the dolls turned to face each other and interacted contingently in pairs. That is, they hierarchically reorganized the set of four individual dolls into two *social dyads*. In contrast, when the social dyads were broken in the condition in which the dolls turned outward to face the infant, infants had no basis on which they could subdivide the array into social groups.

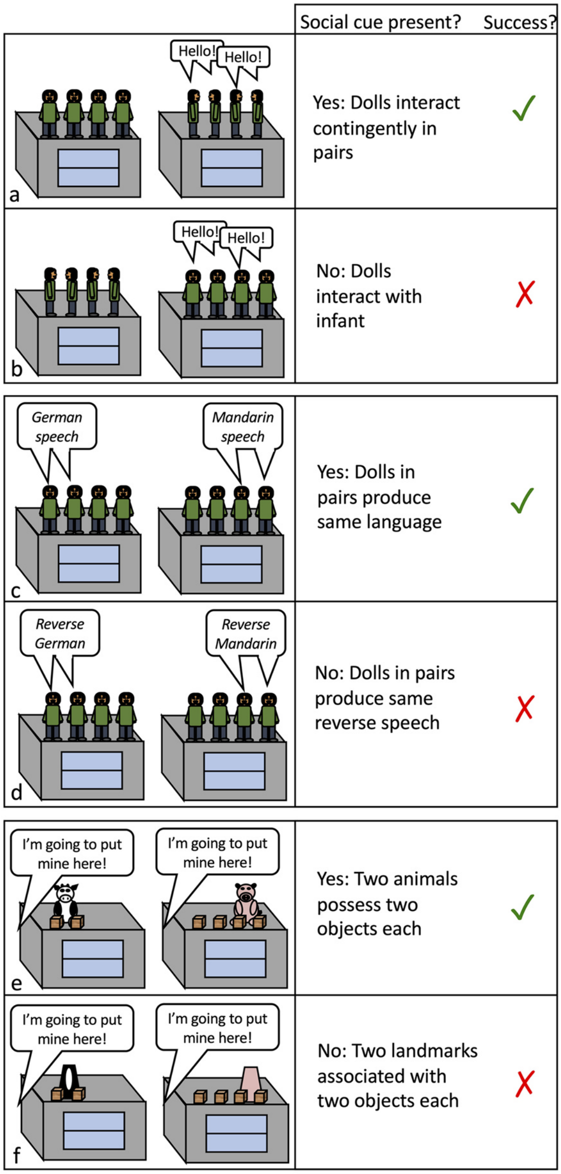


Fig. 4 Schematic examples of studies examining infants' use of social cues to overcome capacity limits on representing object quantities using the manual search task. Panels a and b show schematics of trials from Stahl & Feigenson (2014) in which infants use cues of contingent social interaction to remember four dolls; panels c and d show schematic trials from Stahl & Feigenson (2018) in which infants use cues of shared linguistic group membership to remember four dolls; panels e and f show schematic trials from Stahl et al. (2023) in which infants use cues of ownership to remember four blocks.

Can infants use more abstract social cues to overcome representational capacity limits? In another study, we asked whether infants can make sophisticated inferences about social group membership, even in the absence of contingent interaction, in order to overcome representational limits (Stahl & Feigenson, 2018). Previous studies have shown that infants attend to distinctions between languages from birth (e.g., Mehler et al., 1988; Moon, Cooper, & Fifer, 1993), prefer to interact with and learn from native over foreign speakers (e.g., Buttelmann, Zmyj, Daum, & Carpenter, 2013; Kinzler, Dupoux, & Spelke, 2007; Kinzler, Dupoux, & Spelke, 2012), and infer that those in the same linguistic group should share preferences and interact prosocially (e.g., Liberman, Woodward, & Kinzler, 2016; Liberman, Woodward, Sullivan, & Kinzler, 2016). Thus, we investigated whether infants would reorganize their object representations into language-based sets, when individuals within a set spoke the same language. We again presented 16-month-olds with four equally spaced identical dolls, but all of the dolls faced outward. The experimenter then lifted one doll at a time, as a computer underneath the table played a sentence in either English (the infants' native language), or German or Mandarin (languages with which the infants were not familiar)—this gave the illusion that each doll was speaking (Fig. 4, panel c). The dolls were then hidden inside of the box, and infants were allowed to retrieve a subset of the dolls or all of the dolls. When two dolls produced one language, and the other two dolls produced another distinct language, infants continued searching inside the box for the remaining dolls, compared to when the box was empty. This pattern of results emerged when one pair of dolls produced English and the other pair produced a foreign language (German or Mandarin), but also when each pair of dolls produced distinct foreign languages (one set produced German and the other set produced Mandarin). Importantly, infants were not merely using shared low-level acoustical cues between pair members as a basis for chunking. When dolls within a pair produced the same utterances but in reverse (i.e., two dolls produced reverse German speech, and two dolls produced reverse Mandarin speech), infants failed to keep track of all four dolls (Fig. 4, panel d). Thus, 16-month-olds are able to harness their knowledge of social group membership to hierarchically reorganize their mental representations of four social objects into two social groups based on the language individuals speak, an important marker of group membership.

The aforementioned studies examined how infants can overcome their representational capacity limits using social information *between* agents—that is, agents that interact with one another or share group membership. However, as discussed in Section 3, agents often interact with objects in a social context. In a recent study (Stahl et al., 2023), we asked whether infants could utilize the relationships between social agents and objects to bind those objects into sets, thereby overcoming representational capacity limits. We focused on the cue of ownership—that is, the understanding that agents can be the owners of objects.

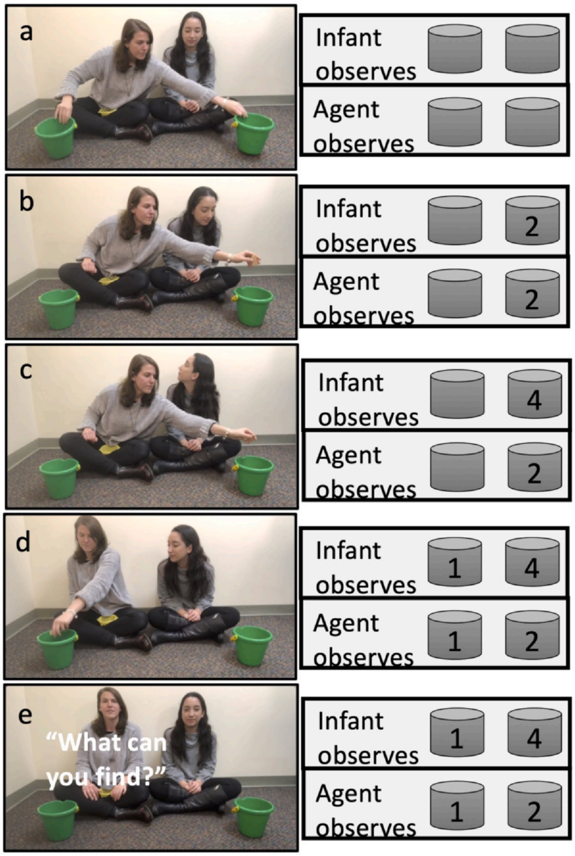
Understanding ownership can be particularly challenging, because ownership relations are abstract and often not directly perceptible—for example, an individual can own an object with which they have no physical contact (e.g., I can own my computer that is twenty miles away in my office). Previous studies have shown that older children understand nuanced ownership relations (see Nancekivell, Van de Vondervoort, & Friedman, 2013; Nancekivell, Friedman, & Gelman, 2019 for reviews), and that infants understand and produce possessive language (e.g., Hay, 2006; Ross, Friedman, & Field, 2015; Saylor et al., 2011). We asked whether infants can mentally reorganize their object representations based on ownership relations. Sixteen-month-olds saw two distinct agents (a cow and a pig) each appear to possess identical blocks. In some cases, the agents physically held and placed each block on top of the box while saying, "I'm going to put mine here." In other cases, the animals sat on the box and the experimenter placed the blocks in front of the animals using the same utterance (Fig. 4, panel e). In both cases, it appeared that the cow owned two blocks, and the pig owned two blocks. The infants then saw all four blocks, equally spaced apart, before being hidden inside of the box. Infants then retrieved either some or all of the blocks from the box. Infants persisted in searching inside the box when only a subset was retrieved, but not when all of the blocks were retrieved, demonstrating that they represented the four individual blocks as two sets of two blocks, each owned by distinct agents. Infants were not simply using the animals as perceptual landmarks with which to group the objects (e.g., two blocks sit in front of the black and white object, and two objects sit in front of the pink object)—when all aspects of the experiment remained the same but the animals were replaced with perceptually-matched inanimate objects (i.e., a fuzzy black and white cylinder, a fuzzy pink cylinder), infants failed to represent all four blocks that were hidden inside of the box (Fig. 4, panel f). These experiments demonstrate that infants can represent the social context of objects (i.e., ownership relationships between agents and objects), and use those representations to overcome their capacity limits.

Together, this work suggests that infants can use social content and context to hierarchically restructure their memory representations into more efficient groups, thereby remembering more than they otherwise could. Our lab is now investigating whether other social cues prompt infants to restructure their memory representations, by spontaneously forming social groups based on shared traits (e.g., dolls who have similar vs. different preferences).

4.4 The social world shapes infants' capacity to represent object quantities: Keeping track of subsets

Previous work showed that infants attend to others' visual perspectives (e.g. Choi et al., 2018; Reid et al., 2004; Wahl et al., 2013), and an agents' perspective may even take precedence over infants' own perspective in contexts in which an agent has a different belief than the infant about whether an object is hidden in a location (Kampis et al., 2015; Kampis, 2017). In recent work, we (Applin and Kibbe (in preparation)) asked whether infants who are tasked with tracking four objects—outside of their signature object tracking limit—could use another agent's partial knowledge of the contents of the array to help support their own representations and prevent catastrophic representational failure. For example, if four objects were hidden in a location, but an agent was aware of only two of those objects, would infants use the agent's representation instead of their own to track the objects?

To answer this question, we combined the ordinal choice method of Feigenson et al. (2002, see Fig. 2) with the concept behind Kampis et al. (2015), in which the infant and the agent have different perspectives on the contents of a location. In our studies, 11–14-month-old infants observed an experimenter distribute quantities of graham crackers across two opaque containers such that one container always contained more than the other (Fig. 5, panels a–d). One bucket always contained more crackers than the other. Our critical variation on this task was the presence of an agent who observed the experimenter's actions along with the infant. Before the experimenter placed crackers in each container, the agent turned her attention to that container by saying "Ooh!", physically moving her head, and leaning slightly toward the bucket. The Agent then watched as the experimenter placed the crackers in the container (Fig. 5, panels b and d). Crucially, when the experimenter was distributing the *larger quantity*, the agent watched as some of the crackers were hidden, and then became "distracted" (saying "Oh!" and looking up and over her shoulder, away



Infant observes	Agent observes	Success?
4 vs. 1	2 vs. 1	✓
4 vs. 1	*Eyes closed*	✗
4 vs. 2	2 vs. 2	✗

Fig. 5 The top panel depicts the sequence of events from Experiment 1 of Applin and Kibbe (in preparation), along with the quantities that were inside of the containers at each time point. The bottom panel shows infants' patterns of success across the three experiments, depending on the agent's perspective on the contents of each location.

from the containers) while the experimenter finished hiding the remaining crackers (Fig. 5, panel c). Thus, the Agent observed *only a subset of the crackers in the larger-quantity container*, and all of the cracker(s) in the smaller quantity container.

In Experiment 1 (depicted in Fig. 5), 11–14-month-old infants observed four crackers hidden in one location, and one cracker hidden in the other—quantities which typically induce catastrophic representational failures in infants. However, in our experiment, when the experimenter hid the set of four crackers, the agent watched the first two crackers hidden, and then looked away while the other two crackers were hidden (Fig. 5, panels b and c). Thus, while the infant observed 1 vs. 4 (outside of infants' object-tracking limit), the agent observed 1 vs. 2 (within infants' object-tracking limit). We reasoned that, if infants are influenced by the Agent's representation of the number of objects hidden in each location, they should succeed where they usually fail. Indeed, we observed that infants chose the bucket containing four objects at rates significantly above chance. That is, infants did *not* show the typical signature limit of catastrophic representational failure when they observed that an Agent was aware of only a subset of the objects in the 4-object set.

We next asked whether the results we obtained in our first experiment could be explained by grouping cues triggered by the agent's movement and vocal patterns, rather than the Agent's (partial) knowledge of the quantities of objects in each location. That is, we reasoned that infants could have used the agent's movements or vocalizations as event markers or perceptual grouping cues that helped them to hierarchically restructure the set of four objects into two groups of two. To test this, we conducted a second experiment that proceeded exactly as above, except the agent closed her eyes at the start of the study and *kept them closed throughout*. The agent's motions were thus identical to our first experiment (orienting her head and body toward each bucket during hiding, orienting her head away while the second two crackers are hidden in the 4-cracker bucket), thereby equating the motion cues across experiments while manipulating whether or not the agent could see how many objects are being hidden. If lower-level grouping cues influenced infants' choice behaviors, then our two experiments should produce similar results. Contrary to this, we found that 11–14-month-olds crawled to the buckets at roughly equal rates, consistent with previously observed failures with 1 vs. 4 (e.g. Feigenson et al., 2002), and significantly different from infants' choice behavior when the agent's eyes were open, suggesting that it was the agent's *incomplete knowledge* of the quantity in the 4-object array in our first experiment that prevented catastrophic representational failures in these infants.

Finally, we probed a mechanism for 11–14-month-olds' success when the agent has partial knowledge of the four-object array. We asked whether the agent's partial knowledge of the contents of the array promoted *chunking* of the four-object set into two sets of two based on the agent's representation (into, e.g. [what the agent saw] [what the agent did not see]) or whether it prompted infants to track *a subset* of the objects in the array (e.g. keeping track of two of the four objects in the 4-object array) in order to prevent catastrophic forgetting. This third experiment proceeded similarly to the other two experiments, except that we hid two objects in one location and four in the other. Thus, infants observed 4 vs. 2, while the agent observed 2 vs. 2. If infants use the agent's partial knowledge of the contents of the larger array to promote *chunking*, they should represent all four crackers, and therefore should successfully crawl to the four-object container. However, if infants are using the agent's partial knowledge of the objects to track two of the four-object set, they should represent the containers as holding equivalent quantities, and should crawl to the containers at roughly equal rates. We found that 11–14-month-olds' choices were in line with what would be expected by chance, suggesting that infants may be using the agent's visual access to track a subset of the objects in the larger set (but not all of them)—enough to prevent infants' typical pattern of catastrophic representational failure.

Together, these results suggest that infants' processing of other people's perspectives may impact the way they represent quantities of hidden objects. Our lab is continuing to probe the mechanisms that underlie infants' patterns of behavior in these experiments. For example, we are asking whether infants are using the agent's representation *instead of* their own, or whether the agent's representation helps infants to attend to and track a subset of the objects themselves. We are also asking whether the influence of the agent's representation of the array is *automatic*, happening any time an agent is present (as predicted by Southgate, 2020), or whether this influence is only felt when infants' representational limits are exceeded; that is, when they lose track of their own representations and may therefore rely on the agent's perspective instead.

5. Conclusions

The social world shapes the way infants represent objects, from identities to quantities. When objects are *socially relevant*—imbued with social content or presented in social contexts—infants represent those objects differently than when objects are presented without social information. Indeed, we showed that when objects are socially relevant, the seemingly consistent signature limits measured in non-social contexts can shift. Sometimes the social relevance of objects helps infants *overcome* signature limits, representing more object identities (as in Kibbe & Leslie, 2019) or more individual objects (as in Applin & Kibbe, in preparation; Stahl & Feigenson, 2014, 2018; Stahl et al., 2023) than in non-social contexts. However, sometimes attending to and interpreting the social context in which objects are embedded results in fewer resources available for representing objects (as in Applin & Kibbe, 2019), suggesting that representing agents and their dispositions toward objects can sometimes be prioritized over representing the details of the objects themselves.

Studying infants' object representations within a social framework can provide answers to some puzzling aspects of early cognition. Previous work that examined infants' object representational capacities in non-social contexts revealed limitations so significant that it is difficult to imagine how infants might be able to hold enough information about the world in mind at once to acquire new knowledge about the world. However, while these limits may appear rigid, fixed, and restrictive in non-social contexts, placing objects in socially relevant contexts reveals a more nuanced and dynamic picture. The research we reviewed here suggests that infants are able to flexibly integrate social relevance into their processing of objects in the world, and can assess the social roles of objects when deciding how to allocate limited representational resources across the agents and objects in social scenes. For infants with limited representational capacities, the challenge of learning about the world becomes more surmountable when they are able to use the social environment in which they are embedded to organize and prioritize incoming information about objects.

We focused on the impact of social content and context on infants' *object* representational limits, but we suspect that the social world may impact a range of capacity-limited systems in infancy (and beyond), from representations of approximate quantities to executive functions. We suggest that, to build robust, accurate, and ecologically valid models of foundational capacities in infant cognition, researchers should take infants' social environments into account.

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